

# Acoustic Model Testing Chronology

ER42/ Tom Nesman

Spacecraft and Launch Vehicle

Dynamic Environments Workshop, June 20-22, 2017

Scale models have been used for decades to replicate liftoff environments and in particular acoustics for launch vehicles. It is assumed, and analyses supports, that the key characteristics of noise generation, propagation, and measurement can be scaled. Over time significant insight was gained not just towards understanding the effects of thruster details, pad geometry, and sound mitigation but also to the physical processes involved.

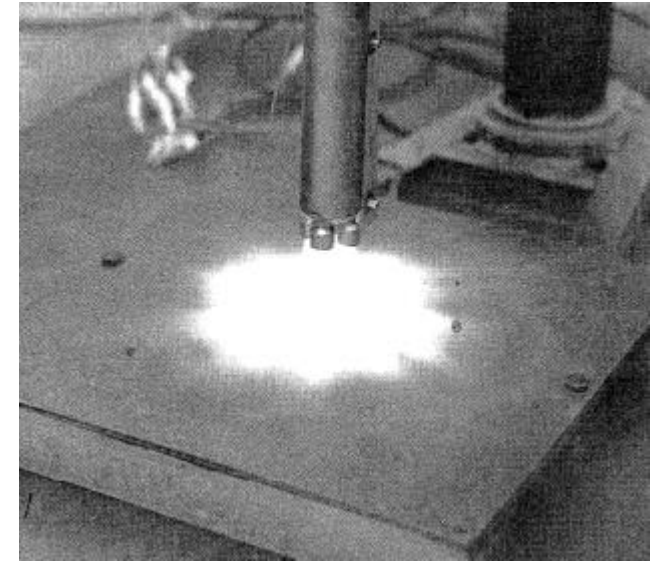
An overview of a selected set of scale model tests are compiled here to illustrate the variety of configurations that have been tested and the fundamental knowledge gained. The selected scale model tests are presented chronologically.

- Early acoustic model testing (1950's) explored a multitude of deflector, launch duct, and launch pad configurations
- These early tests also tried various water sprays ... initially for cooling but an additional benefit, reduction in acoustics, was observed
- Later, vehicle specific acoustic scale model testing was conducted

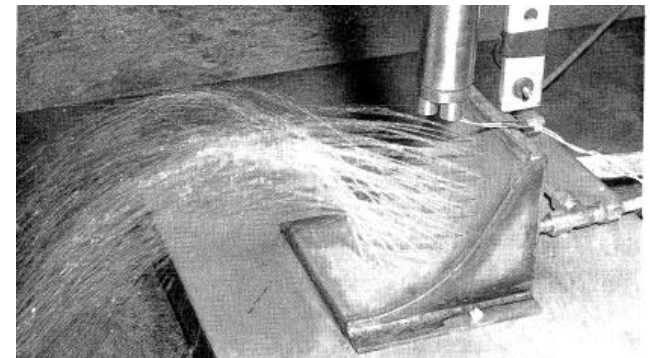
# 1959 Rocket/ Pad Acoustic Model Studies

Ref: Sugamele, J., and Sutherland, L.C., "Acoustic Model Rocket Studies," Boeing Report Number D5-4457, March 30, 1960

- Model solid fuel rocket & supersonic cold air jets
  - Both give same *qualitative* trends
- Multiple launch pad designs versus noise level
- Low frequency octave band levels increasing relative to overall sound levels as the vehicle rises
- Sound field of full scale rocket duplicated only by using a model rocket which duplicates rocket exhaust conditions
- Type of launch pad has little effect on sound levels when vehicle reaches a height of 4 *equivalent nozzle* diameters above pad
- Also noted effects from:
  - Jet impingement angle
  - Introduction of water from deflector surface
  - Elbow deflector with water
  - Deflected multiple nozzles
  - Interaction of multiple supersonic air jets



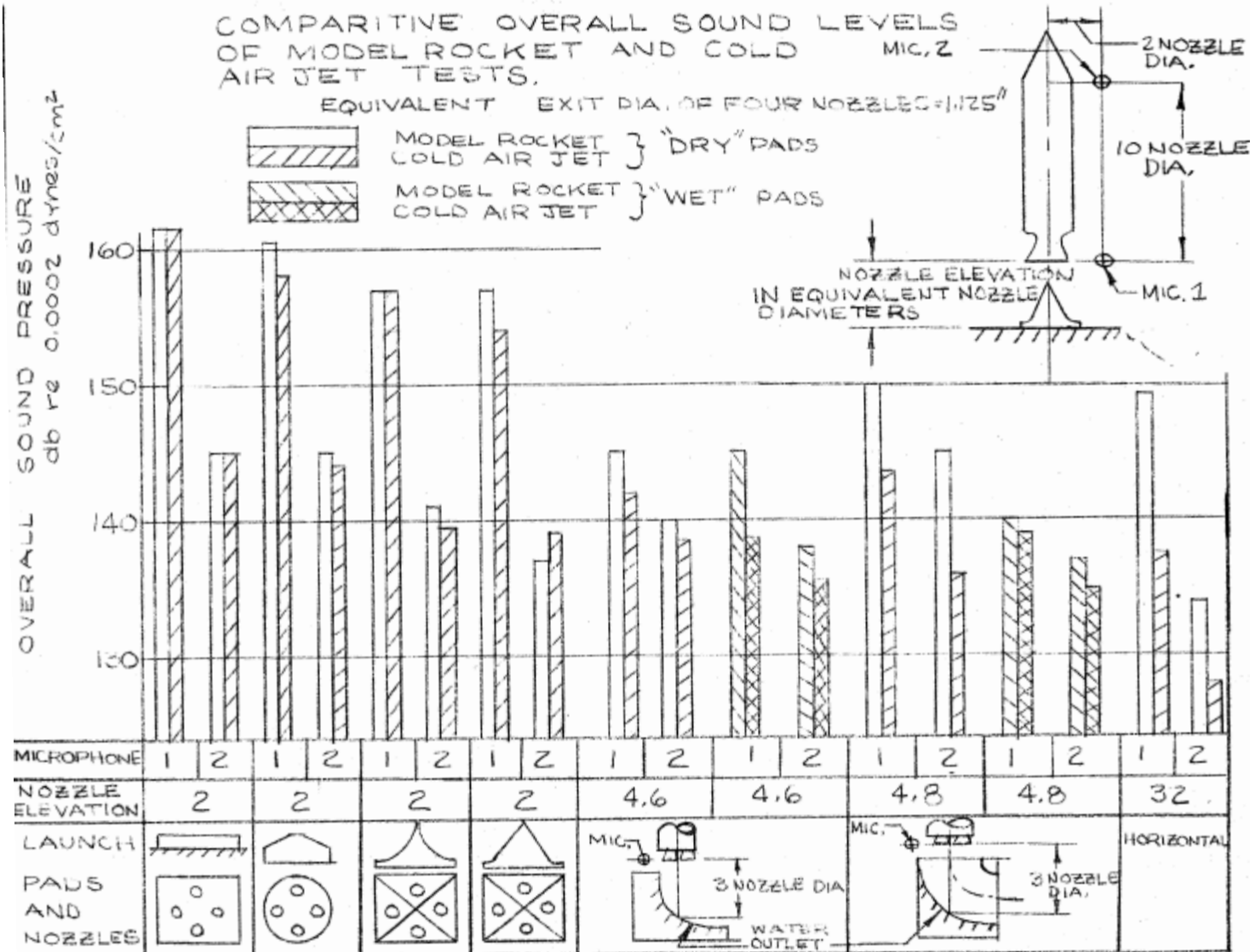
model solid fuel rocket



water from deflector surface

# Overall Sound Level Comparison

Ref: Sugamele, J., and Sutherland, L.C., "Acoustic Model Rocket Studies," Boeing Report Number D5-4457, March 30, 1960



- Scaling model to full scale
  - Model rocket data compared to full-scale with comparable specific impulses and chamber pressures showed a reasonable agreement in absolute magnitude and spectrum shapes by using a frequency scale factor equal to the square root of the relative thrusts
- Atmospheric sound absorption
  - Noted air absorption losses for small acoustic models, e.g., on the order of 5 dB at 50 KHz at a distance of 10.0 feet
- Investigators at this time evaluated physical relationships by comparison of measured data from model and full-scale firings and concluded:
  - Scaling and prediction techniques can provide a reasonable estimate of launch environment
  - There is a relationship between the generated sound energy and the kinetic exhaust stream energy of the rocket engine
  - Prediction of a noise spectrum can be made from engine nozzle diameter and exhaust velocity



# 1961 Model Acoustics Scaling

Ref: Morgan, W. V., Sutherland, L. C., and Young, K. J., "The Use of Acoustic Scale Models for Investigating Near Field Noise of Jet and Rocket Engines," WADD TR 61-178, Apr. 1961

- Similarity for a scale model near field noise:
  - Similarity of noise generation
  - Similarity of flow
  - Similarity of noise propagation
- Rules to obtain comparable sound levels at scaled frequencies
  - Maintain same  $p'$  within flow ( $\rho \cdot U_c^2$ )
  - Maintain same source velocity characteristic relative to ambient

$$\rho \cdot u^2 \quad \frac{U_c}{c_c} \quad \frac{c_c}{c_0}$$

- Observation from same angle and source diameters from source
- Maintain same geometry of source and nearby reflecting surfaces

$$\frac{p_{r,\theta}^2}{(\rho_j \cdot U_j^2)^2} \propto \left[ \frac{\rho_0}{\rho_j} \right] \cdot \left[ \frac{U_j}{c_j} \right]^4 \cdot \left[ \frac{c_j}{c_0} \right]^4 \cdot \left[ \frac{4\pi}{\beta} \right] \cdot \left[ \frac{d_e}{r} \right]^2 \cdot G_1 \left( \frac{u_j}{c_j}, \frac{c_j}{c_0}, \theta \right) \cdot G_2(Kr)$$

$\beta$  is angle of radiation,  $G_1$  is Directivity factor,  $G_2$  is near field factor

Consider the nozzle discharge coefficient (actual mass flow divided by ideal)

- Figure 1 shows Reynolds number based on throat diameter
- Figure 3 is the basis for figure 1

Ref: Morgan, W. V., Sutherland, L. C., and Young, K. J., "The Use of Acoustic Scale Models for Investigating Near Field Noise of Jet and Rocket Engines," WADD TR 61-178, Apr. 1961

Ref: Simmons, F.S., "Analytical Determination of the Discharge Coefficients of Flow Nozzles," NACA TN-3447, April 1955

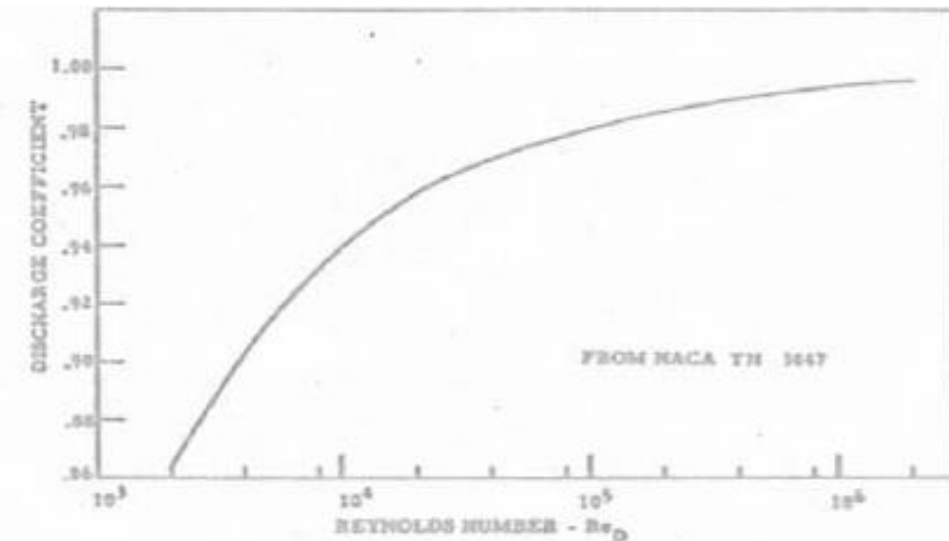


Figure 1. Discharge coefficient as a function of Reynolds number for a typical nozzle.

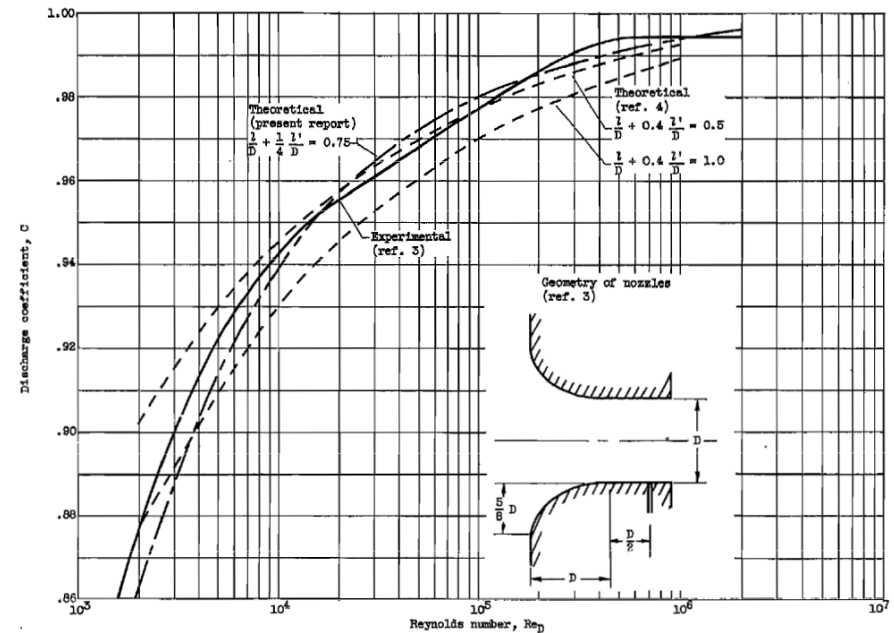


Figure 3. - Comparison of theoretical and experimental curves for discharge coefficients as functions of Reynolds number.



# 1961 List of Vehicle Specific Acoustic Model Tests

*Ref: Morgan, W. V., Sutherland, L. C., and Young, K. J., "The Use of Acoustic Scale Models for Investigating Near Field Noise of Jet and Rocket Engines," WADD TR 61-178, Apr. 1961*

## Full Scale

- Minuteman (solid)
  - Silo
- Jupiter (Lox/ Kerosene)
  - Bucket deflector
- AR-1 Rocket (hydrogen peroxide/JP)
  - Horizontal firing

## Model Scale

- 1/20 scale (solid) tethered (1 sec)
- 1/3 scale (solid) tethered (3 sec)
- 1/20 scale (cold flow) (30 sec)
- 1/36 scale
- 1/8 Scale (gox/ alcohol-water)

# 1961 Saturn I

Ref: Dorland, W.D., "Model Saturn Noise Investigation, Tentative Results of Phase III: Measurement of Simulated Launch Sound Field," Internal Note, MSFC, Dec. 15, 1961

- 1:20 Scale
- Model Saturn noise investigation measurement of simulated launch sound field
- MSFC Component Test Facility, cell 117
- Saturn cluster versus single F-1
- Water on deflector
- Spatial radiation characteristics of the source:
  - distribution of sound energy versus frequency
  - directivity patterns

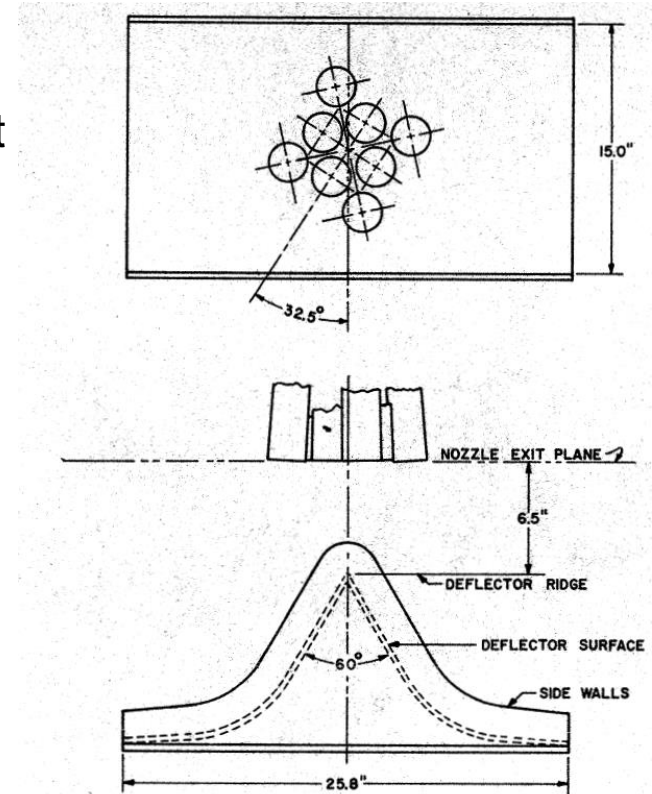


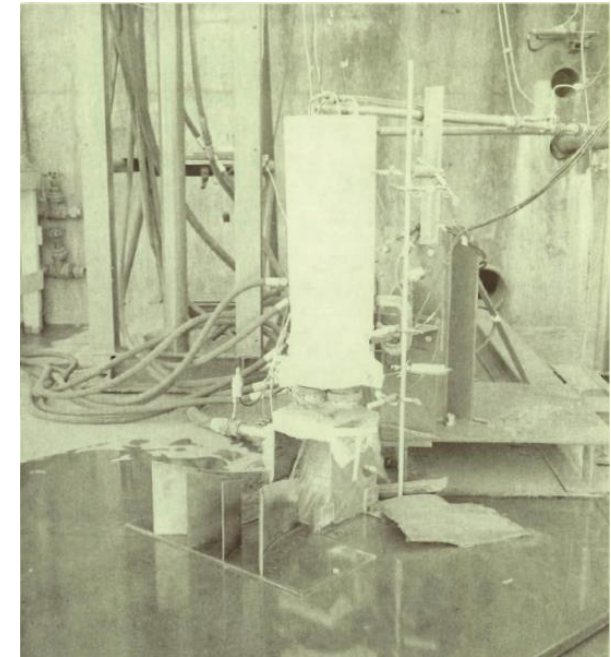
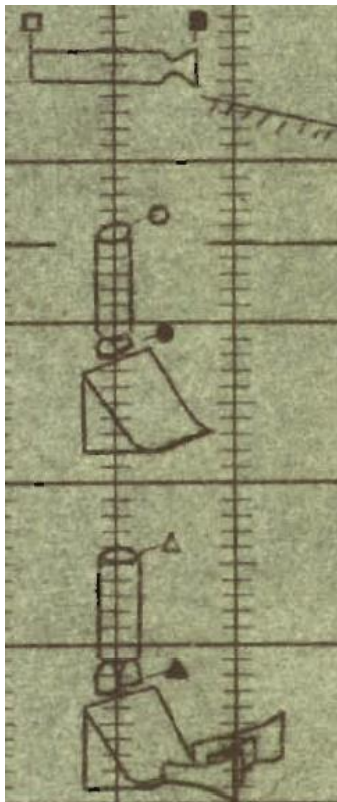
FIGURE 1 - SKETCH OF VLF-34 WEDGE DEFLECTOR

*VLF is Vehicle Launch Facility*

# Saturn IB Scale Model Acoustics

Ref: Sutherland, L. C., "Preliminary Acoustic and Vibration Environment: Saturn IB," Document No. D2-12955,  
Boeing Airplane Company, Dec. 1961

- Simulating an Edwards full scale test
- Horizontal and deflected configurations
- Ramps and vanes



- Microphones
  - At small angle increments for a 105° arc from deflected nozzle exhaust
  - At 4 elevations along rocket



# 1962 624A Solid Propellant Booster

Ref: Van Ert, D., McGregor, H.N. & Hart, P., "624A Scale Model Flame Deflector Program," The Martin Marietta Corporation, Air Force Contract AF 04(695)-54, Jan 1963

- 1:33 scale, Denver test stand D-1, 4 launch elevations
- Full and partial covered duct
  - Duct reduces noise
  - Increased duct length reduces noise
  - Max liftoff at 135' elevation
  - Duct width to encompass drift reduces noise
- Max levels are 5 to 12 decibels lower than with an open flame deflector

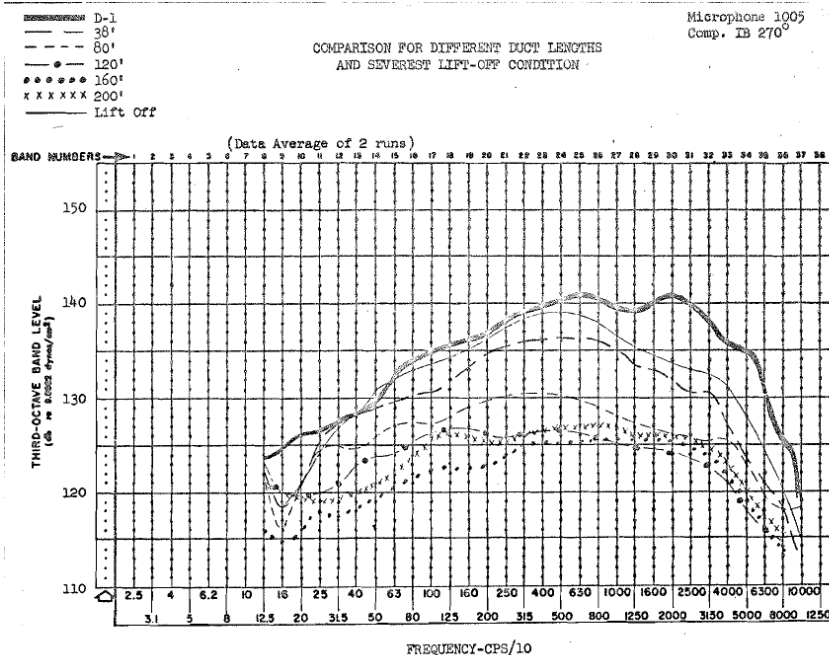
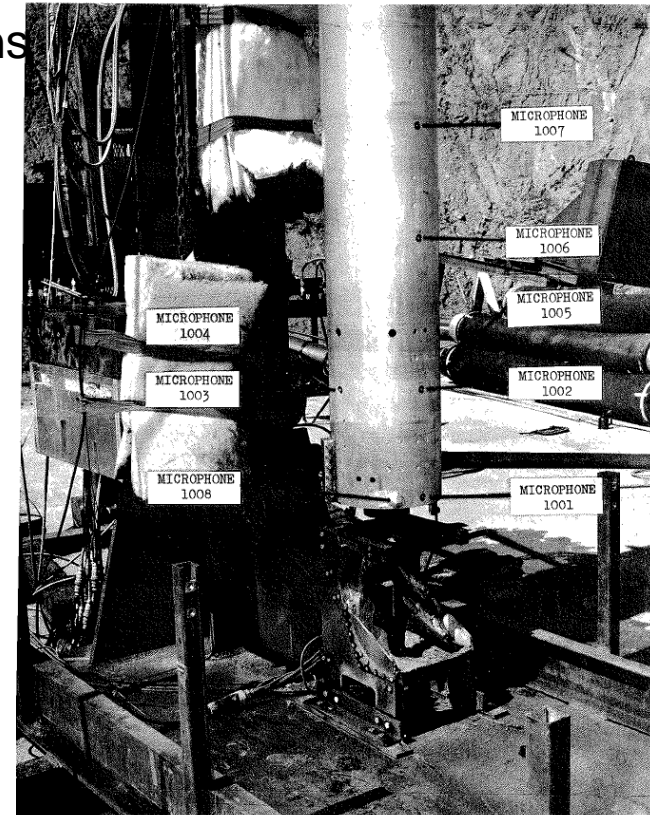
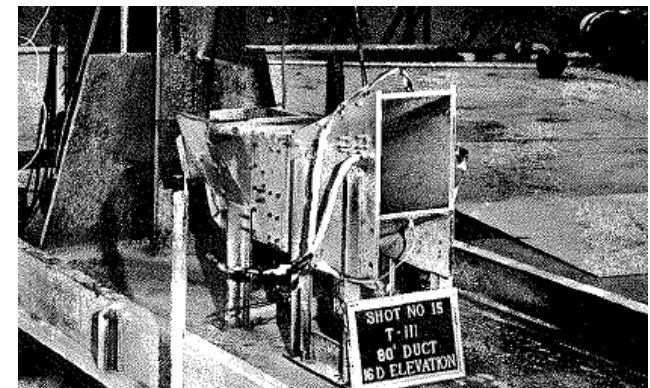


FIGURE 13



# 1964 Scaling Rocket Noise

Ref: Bond, D.A., "A Summary of Model & Full-Scale Acoustic Data for Prediction of Missile Lift-off Noise Environments," Northrop NorAir report NOR-64-215, Sep 1964

**TABLE 1**  
**ASSUMED ENGINE PARAMETERS AND COMPUTED NORMALIZING FACTORS**

Missile/ Model	Thrust lbs x 10 <sup>-3</sup>	Mas W lb	Number of Nozzles	Nozzle Dia. Ft	Eff. Nozz. Dia. D Ft	$\rho_j$ lb/ft <sup>3</sup>	$k_a^{(1)}$ db	$k_f^{(2)}$ ft
Atlas D	352	14	3	2-3.8	5.5	.00783	+2.8	5.64
Jupiter	185	6	1	4.08	4.08	.00629	+4	4.06
Minuteman	164.8	6	1	3.94	3.94	.0072	+3.7	4.07
1/3 Scale Min/Man	20				1.316	.00847	+3.2	1.41
Saturn I	1504	57					+2.9	11.3
Titan I Stg. I	300	1192		8100			+2.5	5.02
Titan I Stg. II	67.3	256		8460			+4.5	2.63
Titan II Stg. I	430	1654		8370				
Titan II Stg. II	87.3	316.8	1	2.74				
1/33 Scale Titan III	1.1	4.92	1	.25				
ASD 1000#JATO	1	4.47	1	.217	.217	.0168		
Augmented Thor	329 < 170 159	680 723	1 3	3.81 1.98	3.43	.009		

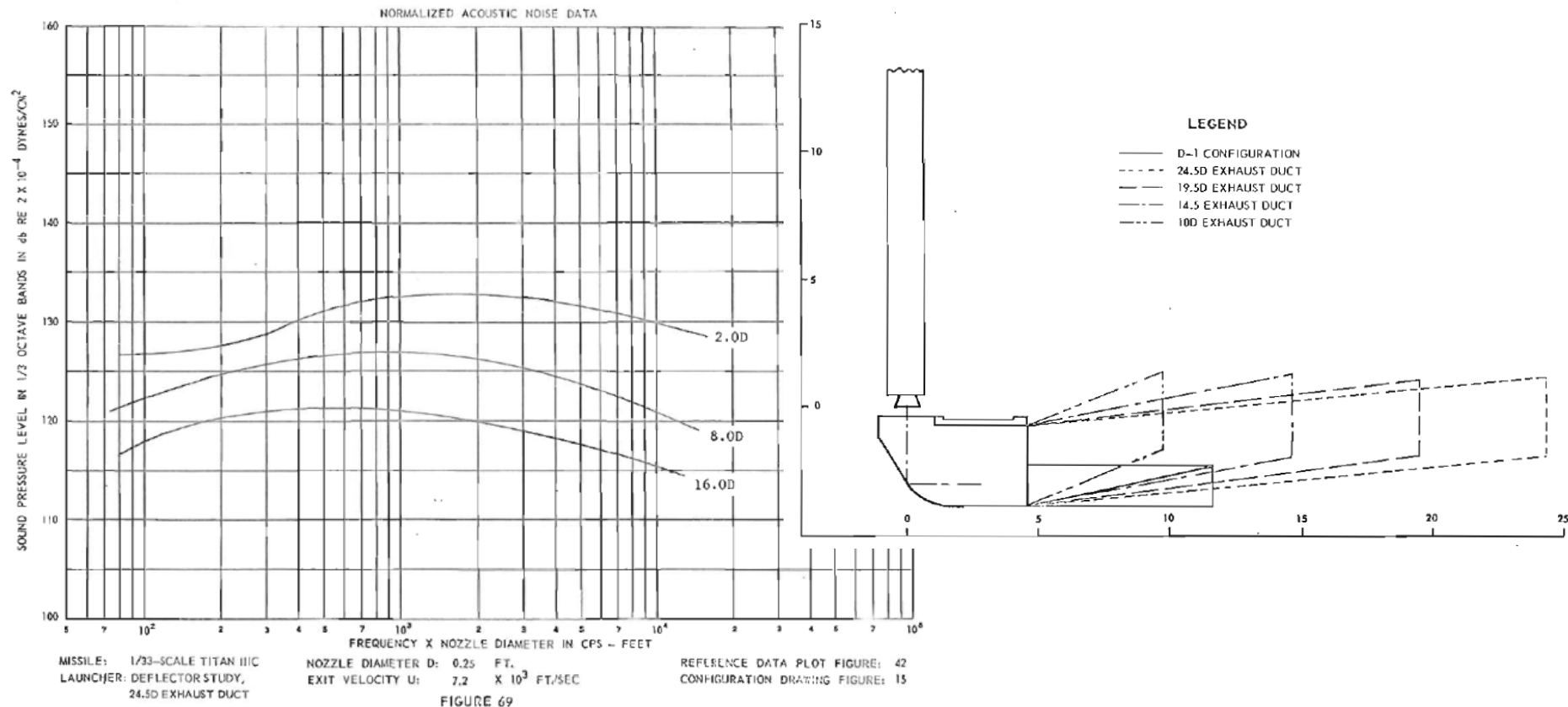
(1) Computed from Equation (13)

(2) Computed from Equation (14)

# 1964 Scaling Rocket Noise: 1:33 Scale Titan III

Ref: Bond, D.A., "A Summary of Model & Full-Scale Acoustic Data for Prediction of Missile Lift-off Noise Environments," Northrop NorAir report NOR-64-215, Sep 1964

- Scale model of the Titan III 120 in. solid rocket motor
- Due to large scale factor (33:1), used only to differentiate effect of long duct
- Later comparison with full scale data showed a favorable result

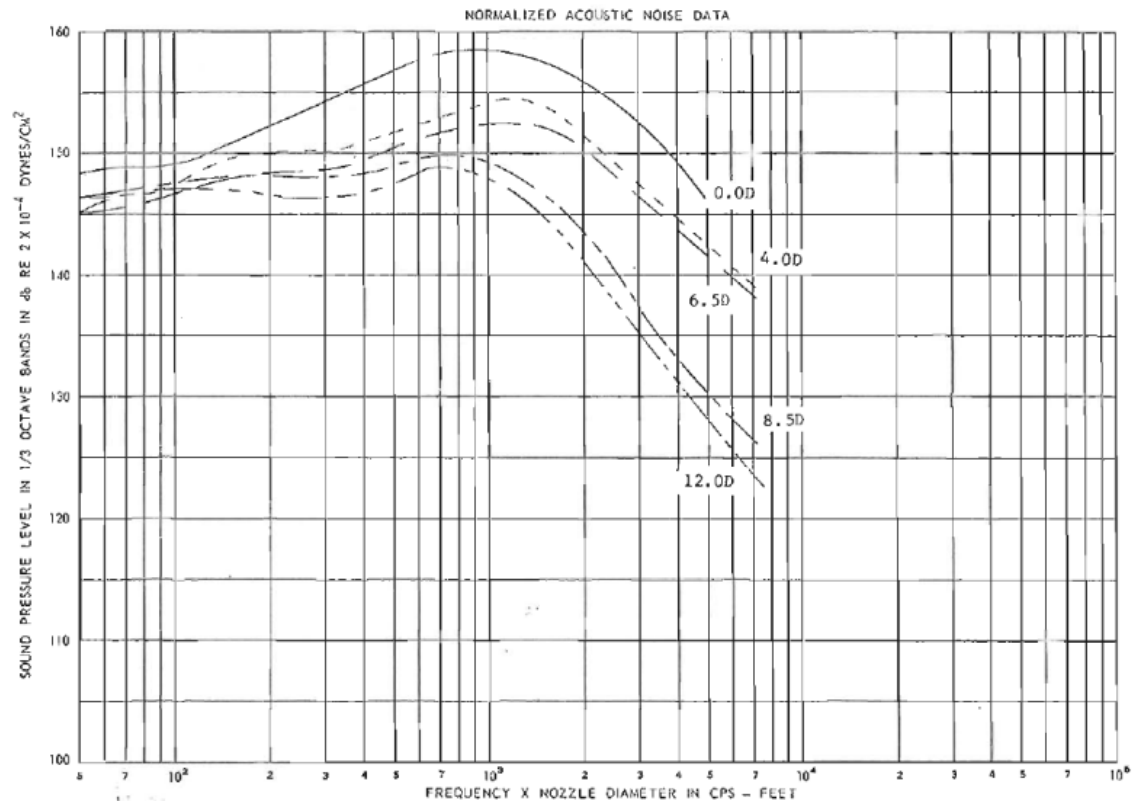
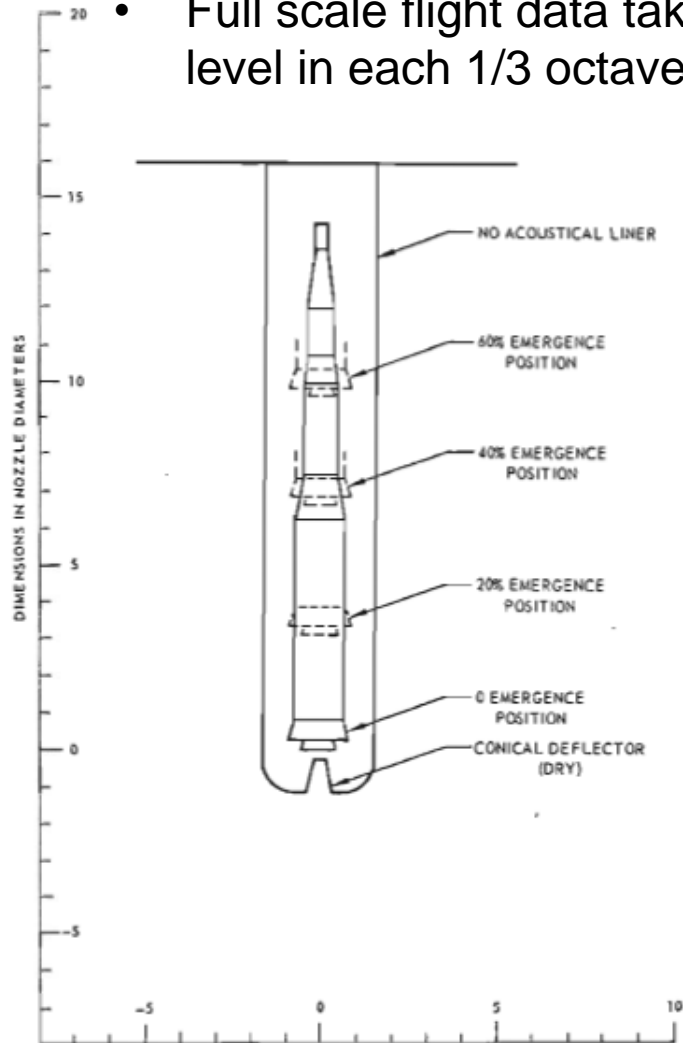




# 1964 Scaling Rocket Noise: 1:3 Scale Minuteman

Ref: Bond, D.A., "A Summary of Model & Full-Scale Acoustic Data for Prediction of Missile Lift-off Noise Environments," Northrop NorAir report NOR-64-215, Sep 1964

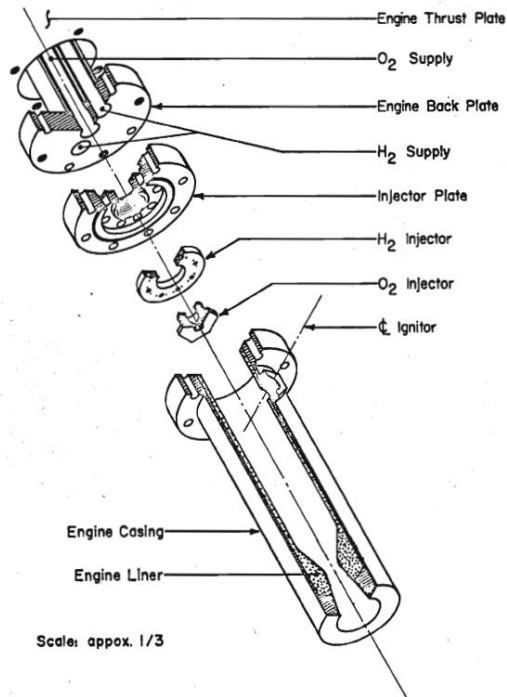
- Scale acoustic model data measured for various points of vehicle emergence
- Full scale flight data taken as missile flies out of silo in the form of maximum level in each 1/3 octave band



# 1966 Lox/H<sub>2</sub> Engine Clusters

Ref: Smith, E.B. and Brown, W.L., "Acoustic Scale-Model Tests of High-Speed Flows, Phase II Final Report,"  
Martin-CR-66-75, Contract NAS8-20223, December 1966

- Horizontal firing: Nearfield & farfield
- One engine design, Multiple engine clusters
- Shift in major spectral peak to lower frequency with larger clusters



PHASE	TEST CONFIGURATION	ENGINE MEASUREMENT	ACOUSTIC MEASUREMENT	
			NEAR-FIELD	FAR-FIELD
I	1 Single-Engine •	10	4	9
	2 Single-Engine •	10	4	9
	3 Single-Engine •	10	4	9
	4 Five-Engine Cluster •••••	14	4	9
	5 Five-Engine Cluster •••••	14	4	9
	6 Five-Engine Cluster •••••	14	4	9
	7 Eight-Engine Cluster ••••••••	17	4	9
	8 Eight-Engine Cluster Circular ••••••••	17	4	9
II	9 Twelve-Engine Cluster ••••••••••••	21	4	9
	10 Twelve-Engine Circular Cluster Canted 15° ••••••••••••	21	4	9
	11 Twelve-Engine Circular Cluster ••••••••••••	21	4	9

- Saturn V uprating test
- 1:58 Scale
- Test position 117A
- Heating rate and surface pressures
- five LOX/RP-1 pressure fed engines
- VLF-39 model
  - Flame trench
  - Flame deflector
  - LUT platform
  - Umbilical tower



*LUT is Launch Umbilical Tower*



## Acoustic Model Test Facility (AMTF)

- Originally built for tests on Saturn models
- Modified in 1974 in for Space Shuttle acoustic model testing
- 6.4% ETR and WTR Acoustic Model Test Programs were conducted at the AMTF
- Open steel test stand structure with a telescoping test article mount
- 180°, 75-meter blacktop area around the stand
- Used extensively in the 1970's and 1980's
- AMTF restored for testing in the 2010's (Constellation & SLS)

*SLS is Space Launch System*

## Test Description

- Shuttle model testing in 2 phases
  - MSFC test lab designed and built 6.4% scale SSME's
  - Tomahawk used as 6.4% scale SRB
  - Phase I - Baseline acoustics and ignition overpressures
  - Phase II - Sound suppression
  - 153 firings
- Requirement for SPL 145 dB Orbiter payload bay internal
  - SSME and SRB contributions
  - Various elevations
  - Noise reduction designs studied
    - In the exhaust trench
    - In the exhaust holes
    - Above deck

## Pad Design Outcome

Developed launch configuration that reduced Shuttle Liftoff Environments to meet payload bay acoustic requirements

- SRB trench side deflectors
- Elongated SRB hole
- SSME hole spray ring
- SRB trench side spray
- Main deflector crest spray
- Deck water spray (rainbirds)

*SSV is Space Shuttle Vehicle*

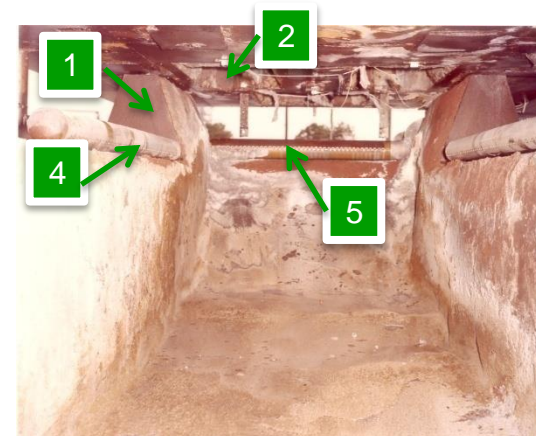
*ETR is Eastern Test Range (Kennedy Space Center)*



# Space Shuttle 6.4% Scale Acoustic Model



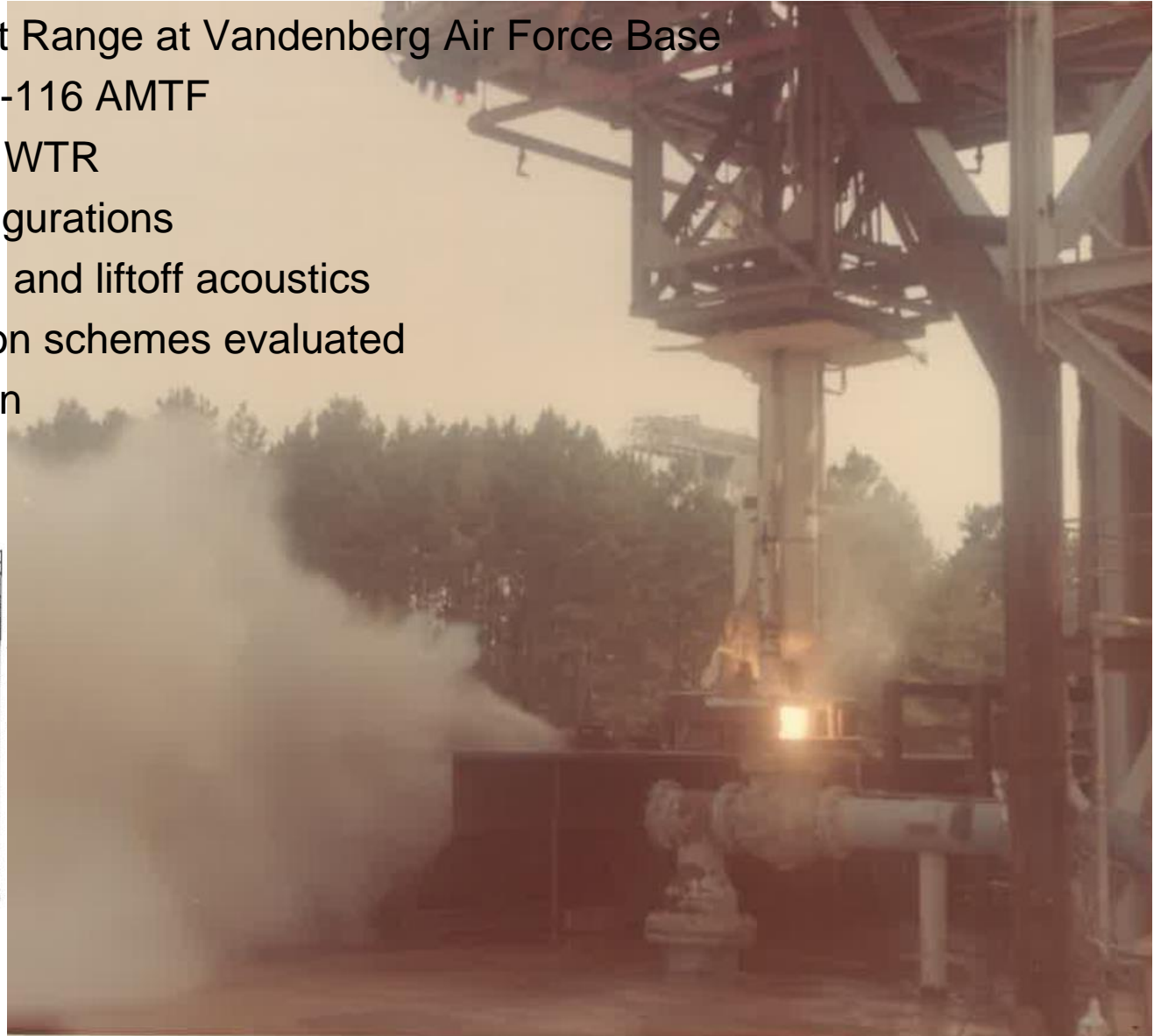
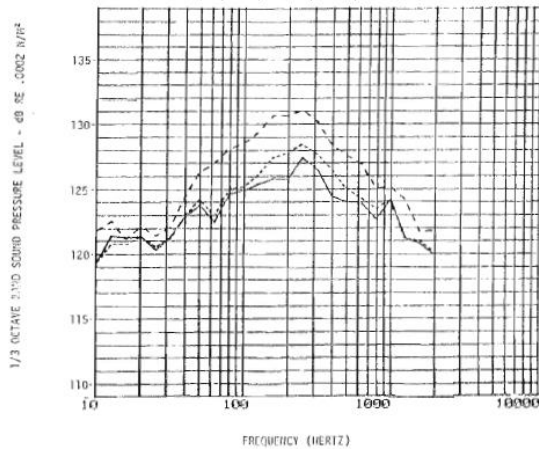
1. SRB trench side deflectors
2. Elongated SRB hole
3. SSME hole spray ring
4. SRB trench side spray
5. Main deflector crest spray
6. Deck water spray (rainbirds)





- WTR is Western Test Range at Vandenberg Air Force Base
- 24 tests at MSFC TS-116 AMTF
- 6.4% scale SSV and WTR
- Plume deflector configurations
- Ignition overpressure and liftoff acoustics
- Various water injection schemes evaluated
- Four tests at elevation

STS EXTERNAL TANK ACOUSTIC LEVELS AT C32  
COMPARISON SHOWING EFFECT OF INJECTION METHOD  
3/1 (SHEET) + 3/1 (U-RING) VS. 6/1 (U-RING)

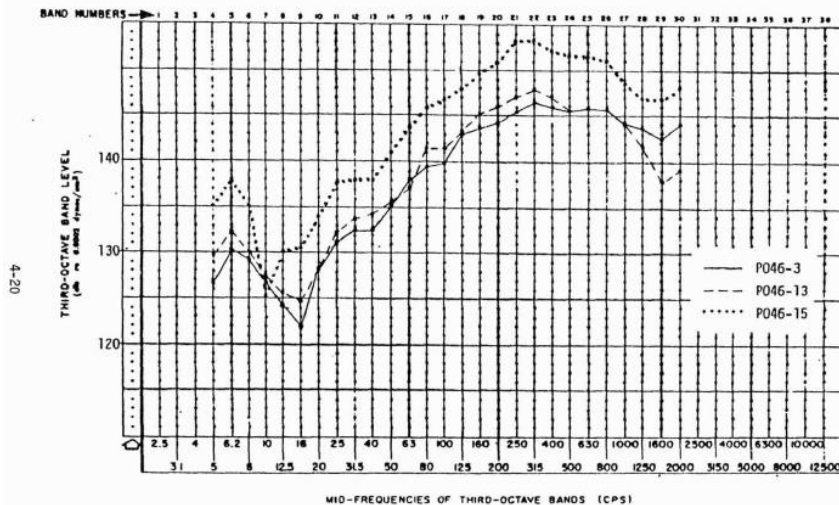


# 1976 SSV WTR (P043)





- Subscale model of Stennis Space Center Main Propulsion Test Article (MPTA) and deflector
- Purpose was to test design and measure effectiveness of spray nozzles intended to reduce engine noise during Shuttle MPTA firing



- TS-116 AMTF
- 4 tests
- 7.5% Scale

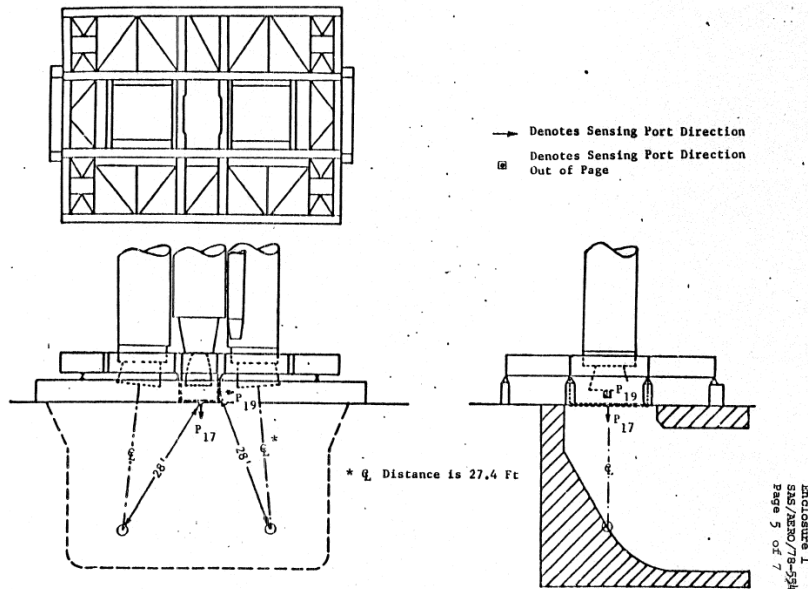
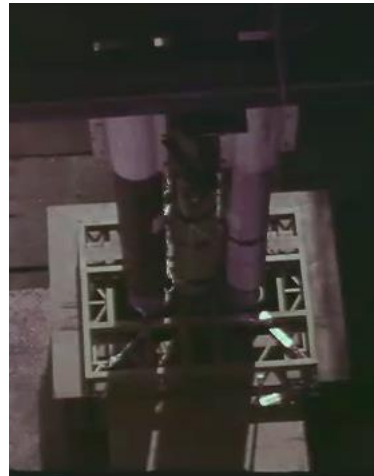
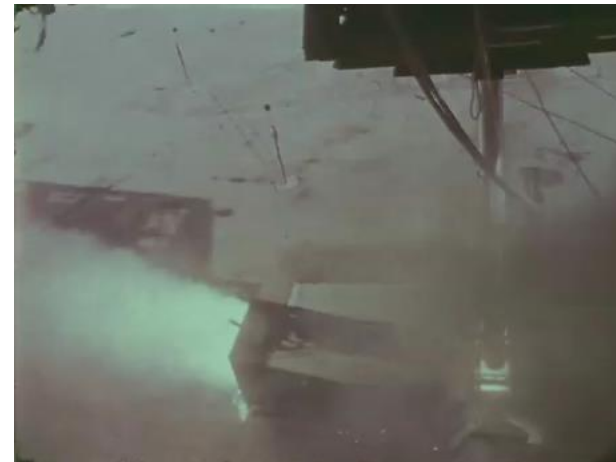
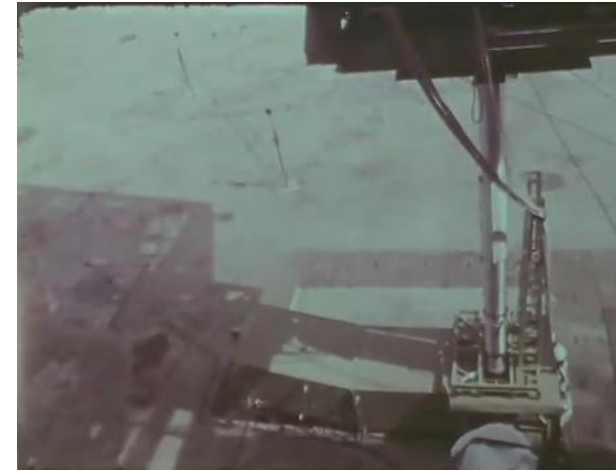
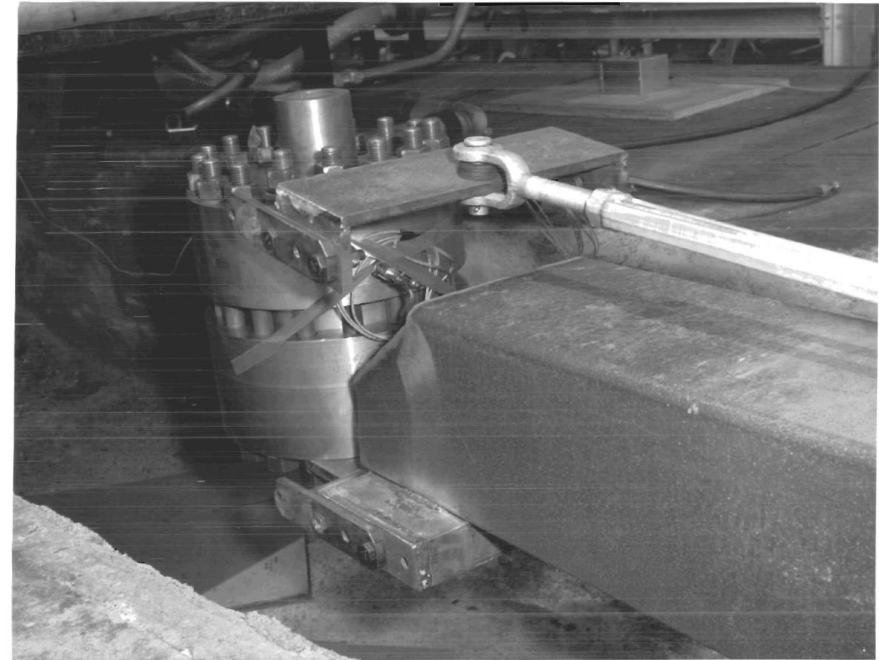


FIGURE 3. DUCT OVERPRESSURE MEASUREMENT LOCATIONS RELATIVE TO SEM NOZZLES.

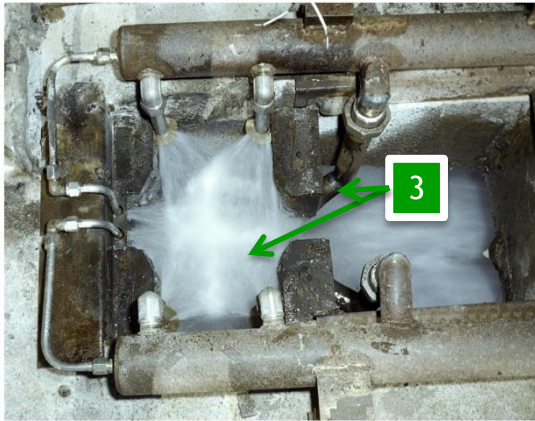


## Test Description

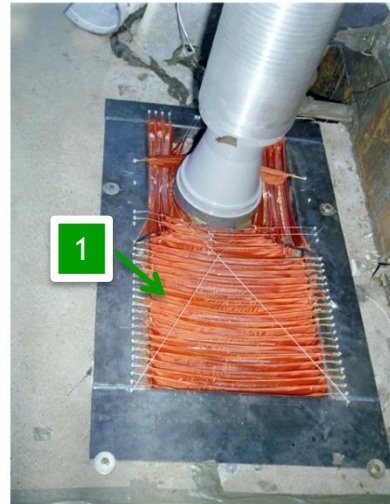
- Testing to design an overpressure suppression system to be installed at KSC
  - SRB ignition is source of overpressure therefore 6.4% scale SSME's not needed
  - Tomahawk used as 6.4% scale SRB
  - 17 popper screening tests →
  - Baseline and suppression tests
  - 38 hot fire tests
  - Splitter plate employed to reduce number of Tomahawks needed
- Requirement to significantly reduce SRB IOP which caused unacceptable loads on orbiter elements during the 1<sup>st</sup> Space Shuttle Launch
- 6.4% scale model ignition overpressure achieved a knockdown of 5 to 8 from STS-1







IMAGE# 8218620 SSVAM 6.4% ETR OVERPRESSURE TESTS WATER SPRAY  
CHECK OUT IN SRB HOLE BEFORE P075-041



IMAGE# 8115175 STS-2 6.4% SCALE MODEL TESTS,  
TOP HOLE SHOWING WATER BAGS SET-UP BEFORE P075-008



IMAGE# 8116436 STS-2 ETR 6.4% SCALE MODEL TESTING P075-036  
& 037 SRB HOLE & WATER BAGS SET-UP BEFORE P075-036

## Pad Design Outcome

1. Water filled hammocks across top of SRB hole (water bags)
2. North trench sidewall water disconnected
3. Water redirected into SRB primary exhaust hole at two elevations





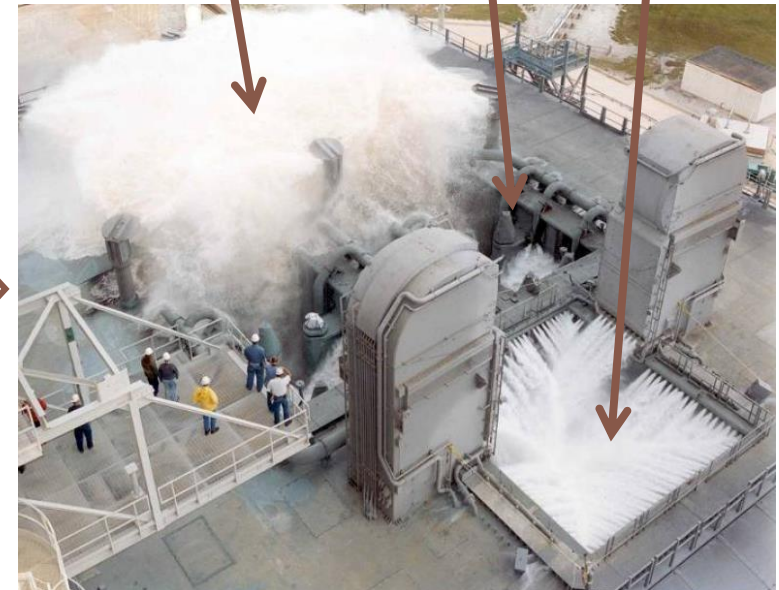
## 6.4% Scale Model Test Calendar

ETR Test Series Begin	Aug 1974
ETR Test Series End	Dec 1976
STS-1	Apr 12 1981
ETR 2 <sup>nd</sup> Series Begin	Jul 1981
ETR 2 <sup>nd</sup> Series End	Aug 1981
STS-2	Nov 12 1981

**Rainbirds**  
(to reduce drift  
impingement  
acoustics)

**SSME Water Ring**  
(to reduce exhaust  
plume acoustics)

**SRB Water  
Injection**  
(to reduce ignition  
overpressure)



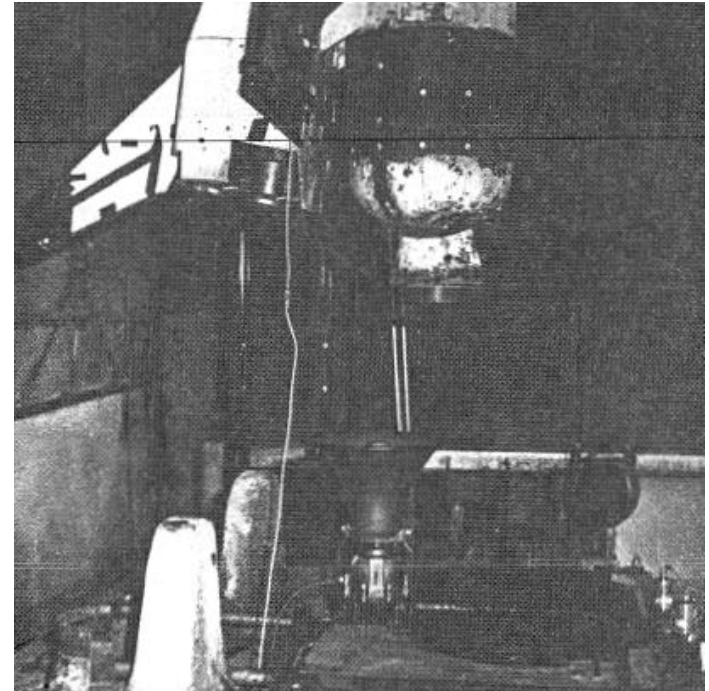
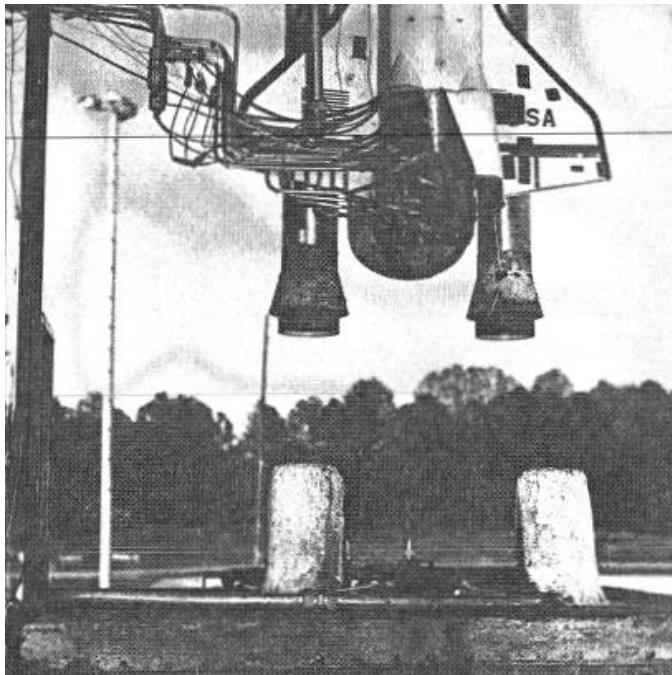
# 1983 SSV WTR (P057)

- 42 tests
- TS-116 AMTF
- 6.4% scale



## 1983 Aft Cargo Carrier (P085)

- 7 tests
- TS-116 AMTF
- 6.4% scale

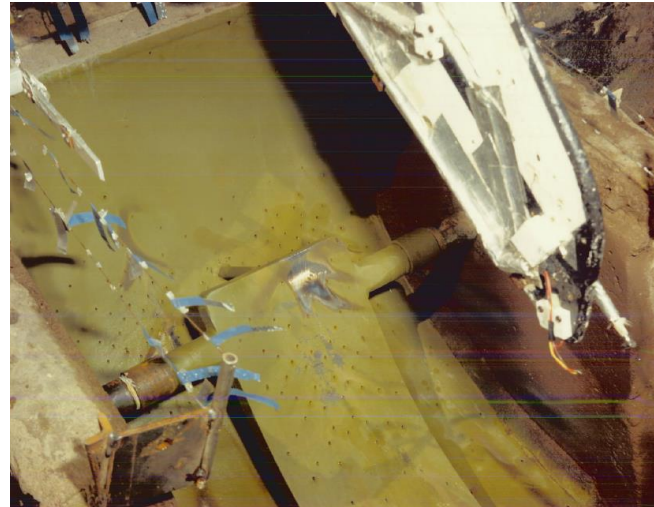


- Aft Cargo Carrier proposed extension of Space Shuttle External Tank to provide additional cargo volume
- acoustic and overpressure data
- test was limited by available SRMs



# 1986 WTR Hydrogen Disposal (P216)

- 76 tests
- TS-116 AMTF
- 6.4% scale
- Acoustics of HDS configurations
  - J-deflector
  - Elbow deflector
  - Max slope deflector
  - Tiered deflector



*HDS is Hydrogen Disposal System*



# 1987 WTR Hydrogen Disposal (P216)

- Steam inerting, SLC-6
- Shuttle Assembly Building in forward parked position
- 6.4% scale steam in SSME duct
- Acoustic, overpressure, and thermal data

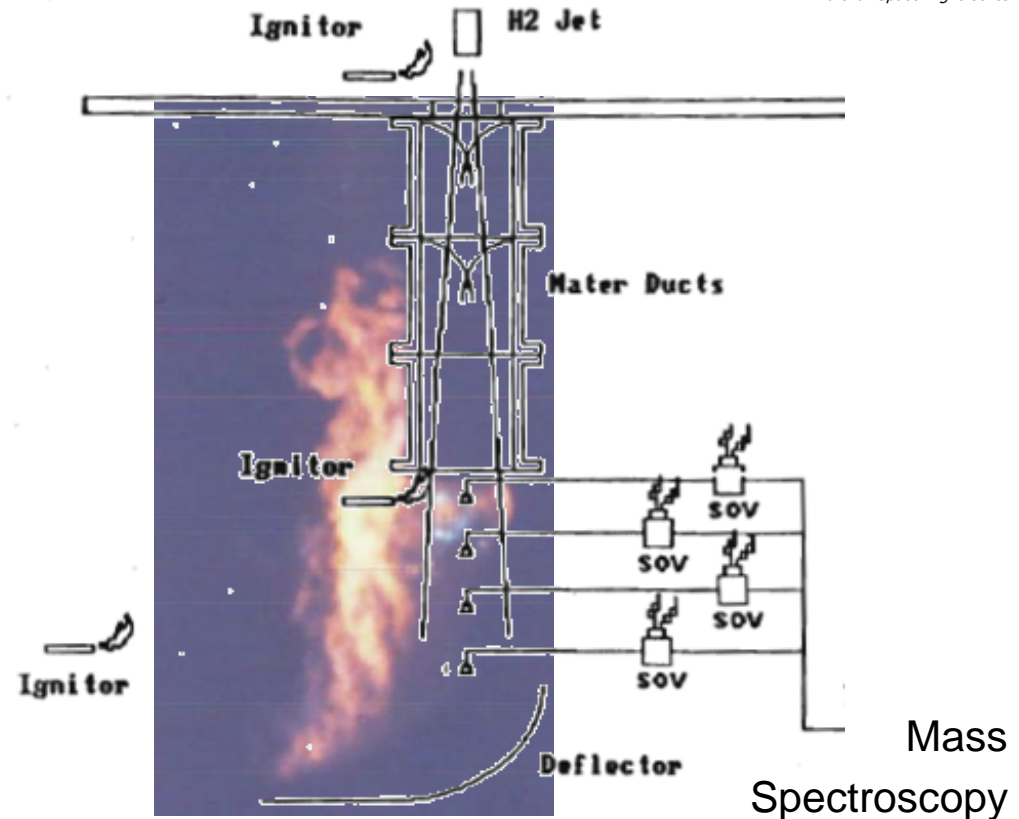


SLC is Space Launch Complex



# 1987 ETR Hydrogen Disposal (P225)

- 45 tests
- TS-116 AMTF
- 6.4% scale

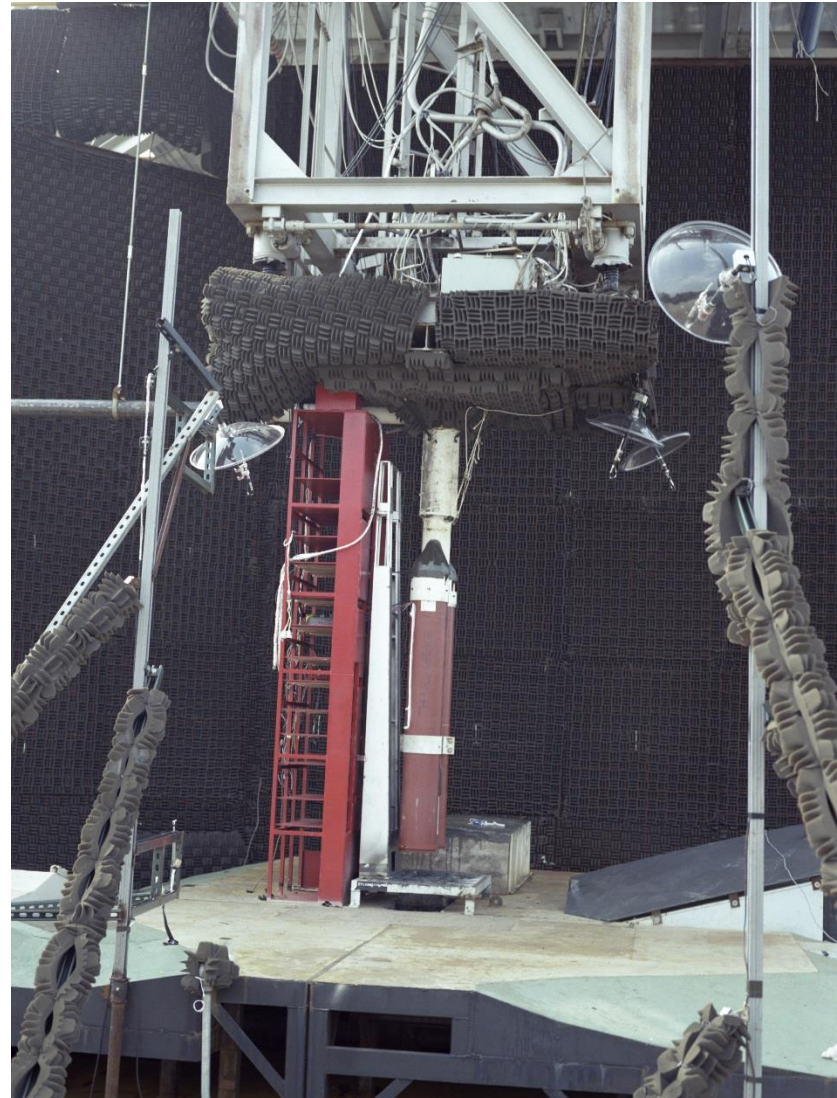


- Determine flame chemistry in time varying turbulent flow
- Use probes to sample flow
- 'On line' determination of chemistry
- Sample gas from water spray/ steam mix
- Determine un-burned hydrogen and residual oxygen



# 1989 Titan IV (P238)

- 5.5% Scale Acoustics
- 63 tests



*Ref: Foulon, H., Gely, D., Varnier, J., Zoppellari, E., Marchesse, Y., "Martel Facility : Simulation of Space Launchers Aeroacoustic Ambiance," AAAF/CEAS, Paris, Nov 29, 1999*

## 1999 Ariane V Scale Model Acoustic Test

- Used MARTEL facility for subscale testing
  - Cold and hot jets to simulate Ariane 5
  - Optimized water injection device at Kourou launch pad
  - Reduced noise radiated at liftoff compared to first flight

*Ref: Gély, D., Elias, G., and Bresson, C., "Aeroacoustic Studies and Tests Performed to Optimize the Acoustic Environment of the Ariane 5 Launch Vehicle," 17<sup>th</sup> International Congress on Acoustics, Rome (Italie), Sep 02-07, 2001*

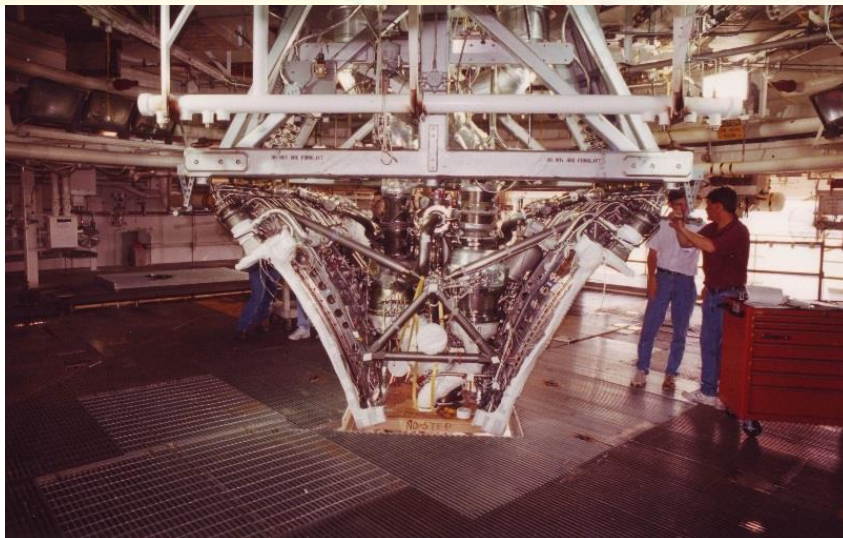
## 2000 Ariane

- 1:47 scale of SRB flue only
- Various flue lengths
- Extended to reduce fairing noise
- The absolute acoustic levels measured in MARTEL facility are not representative of the full scale but the relative levels between several test configurations can be extrapolated.
- Obtained 5 dB reduction

# 1999 – 2001 Linear Aerospike

Ref: Frendi, K., Nesman, T., Wang, T.-S., "A Computational and Experimental Study of Linear Aerospike Engine Noise," AIAA Journal, Vol. 39, No. 8, August 2001

- Multicell thruster and XRS-2200 static test to determine X-33 liftoff acoustics (X-33 is subscale RLV)



- Medium and Heavy configurations
- 1/7 scale RS-68
- Scaled geometry and time by 1/7
  - Full-scale velocity and pressures were matched
  - Sub-scale Cape configuration
- 1999 test at KSC
- 2001 test at Plum Brook



# 2004 Vega & ELA1 at MARTEL Facility

Ref: Gely, Elias, Mascanzoni, & Foulon, "Experimental Acoustic Characterization of the VEGA Launch Vehicle at Lift-off," ONERA TP-05-148, Forum Acusticum EAA Congres, Budapest, Hongrie 28 août-2 septembre 2005

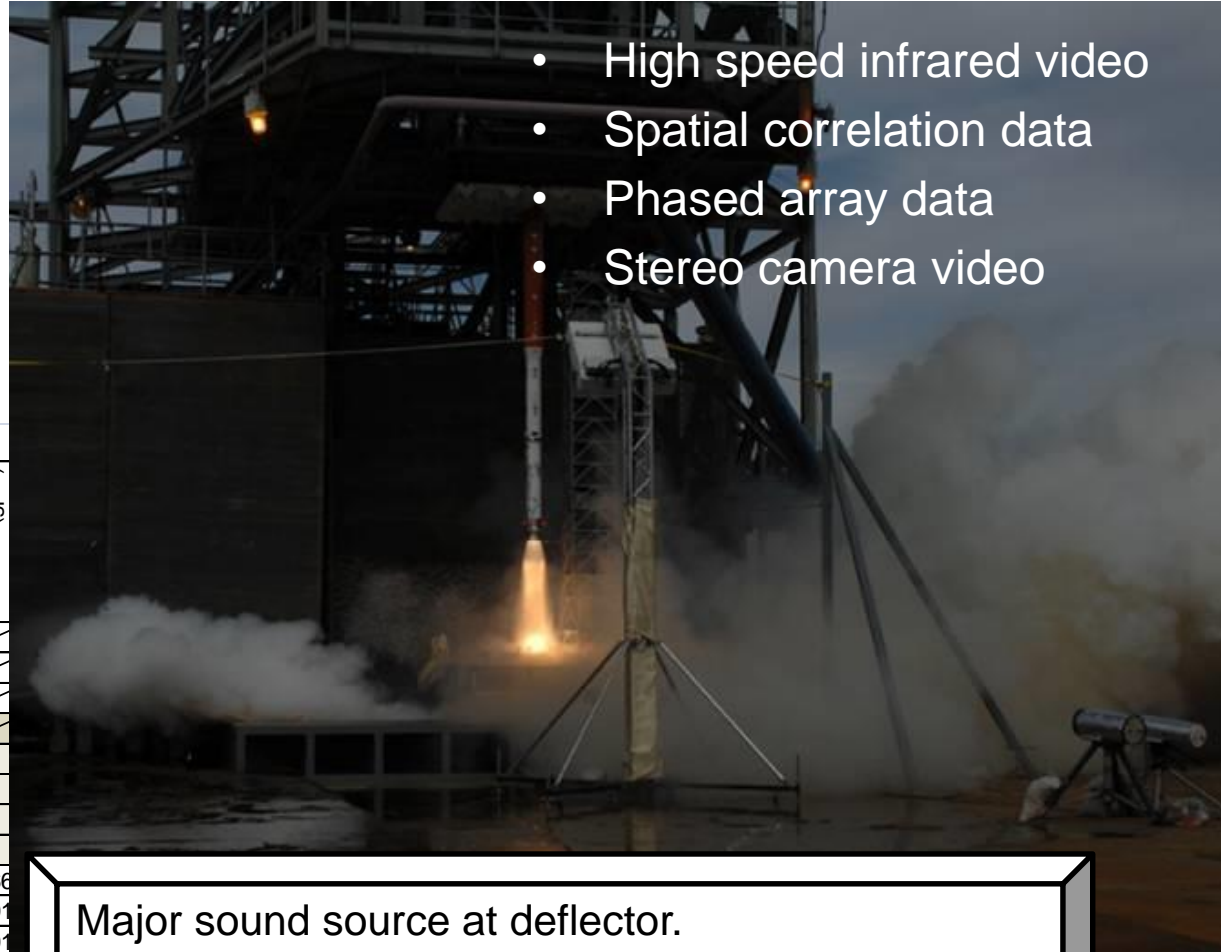
- 1:33 Scale ELA1 launch pad
  - Jet generator for Air-Hydrogen hot supersonic jets
  - Semi-anechoic room
- Cylindrical array with 12-free-field-microphones,
  - Spaced every 60° in azimuth and on two levels
  - Corresponds to fairing level of launch vehicle
- 1:20 Scale of VEGA and ELA1 Launch Pad
  - Facility support structure able to sustain the launcher at different altitudes during the static firing tests
- SRM designed to provide the same acoustic field generated at lift-off by the full scale Vega 1<sup>st</sup> stage SRM
  - Same Strouhal number as P80 full scale motor
  - 41 microphones distributed on vehicle
  - 6 microphones installed on launch pad elements

- IOP studies
  - Titan 34D
  - Commercial Titan
  - Titan IV
- Launch acoustics
  - Atlas 2AS
  - Titan IV
  - Atlas V

# 2010 Ares Scale Model Acoustic Test (P8019)

- 1:20 scale of Ares I rocket
- RATO SRM
- On-deck water schemes
- IOP suppression schemes
- W/ and w/o launch mount


- High speed infrared video
- Spatial correlation data
- Phased array data
- Stereo camera video



Major sound source at deflector.  
Correlation shows that acoustic environment is combination of diffuse and propagating field.

P8019-	Test	Elevation (ft)	Drift (in)	Launch Mount	Waterbags	Trench Water (gpm)	Exhaust Hole Water (gpm)	Rainbird (gpm)
01	HORZ1							
02	VERT1	0	0	Yes	Yes	873	291	
03	VERT2	0	0	Yes	No	873	291	
04	VERT3	0	0	Yes	No	0	0	
05	VERT4	2.5	4.625	Yes		873	291	0
06	VERT5	5	6.875	Yes		873	291	0
07	VERT6	7.5	8.375	Yes		873	291	0
08	VERT7	5	6.875	Yes		873	291	0
09	VERT8	5	6.875	Yes		873	291	566
10	VERT9	5	6.875	Yes		873	291	991
11	VERT10	5	6.875	No		873	175	991
12	VERT11	5	6.875	No		873	175	0
13	VERT12	5	6.875	No		873	175	1275
14	VERT13	5	0	No		873	175	991
15	VERT14	5	0	No		873	175	0
16	VERT15	10	9.875	No		873	175	0
17	VERT16	10	9.875	No		873	175	991
18	VERT17	5	0	No		0	0	0

1040	0	No	Yes	Yes	Yes	Yes	No	6/27/2011	145.7	91.5	50	59%	3	9	253	
2039	3.5	No	Yes	Yes	Yes		Yes	No	6/30/2011	144.0	76.9	76	70%	1	3	248
0	0	No	Yes	Yes	Yes		Yes	Yes	7/12/2011	145.7	87.1		73%	1	4	309



Major sound source at deflector.

Correlation shows that acoustic environment is combination of diffuse and propagating field.



## SMAT Test Matrix

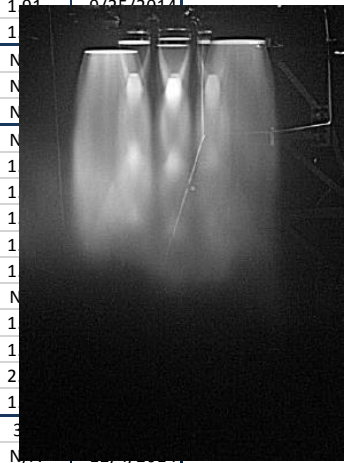
Location		North Trench	10
vation (ft)	Drift (in)	Water (gpm)	
5	10	0	
5	10	0	
5	10	0	
5	10	0	
5	10	0	
5	10	0	
5	10	0	
5	10	0	
5	10	122	
5	10	122	
5	10	122	
5	10	122	
0		680	
0		680	
0		680	
0		680	
0		680	
0		680	
0		318	
0		680	
0		0	
9	4.5625	130	
9	4.5625	130	
9	4.5625	130	
0		0	
0		866	
0		866	
5	10	866	
5	10	866	
5	4.5625	866	
5	2.5	866	
5	2.5	866	
5	2.5	866	
5	2.5	866	
2.5	1.875	866	
7.5	3.75	866	
9	4.5625	866	
7.5	6.125	866	
5	2.5	866	
0		0	



Total Water (gpm)	Rainbird $m_w/m_p$	Date Completed
213	2	1/16/2014

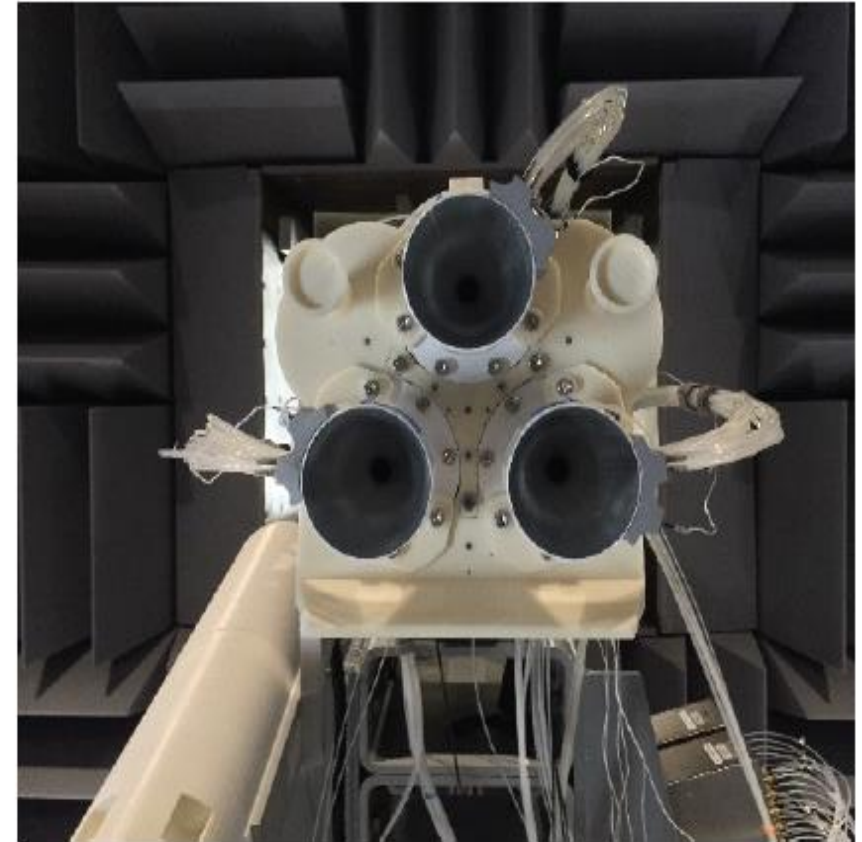
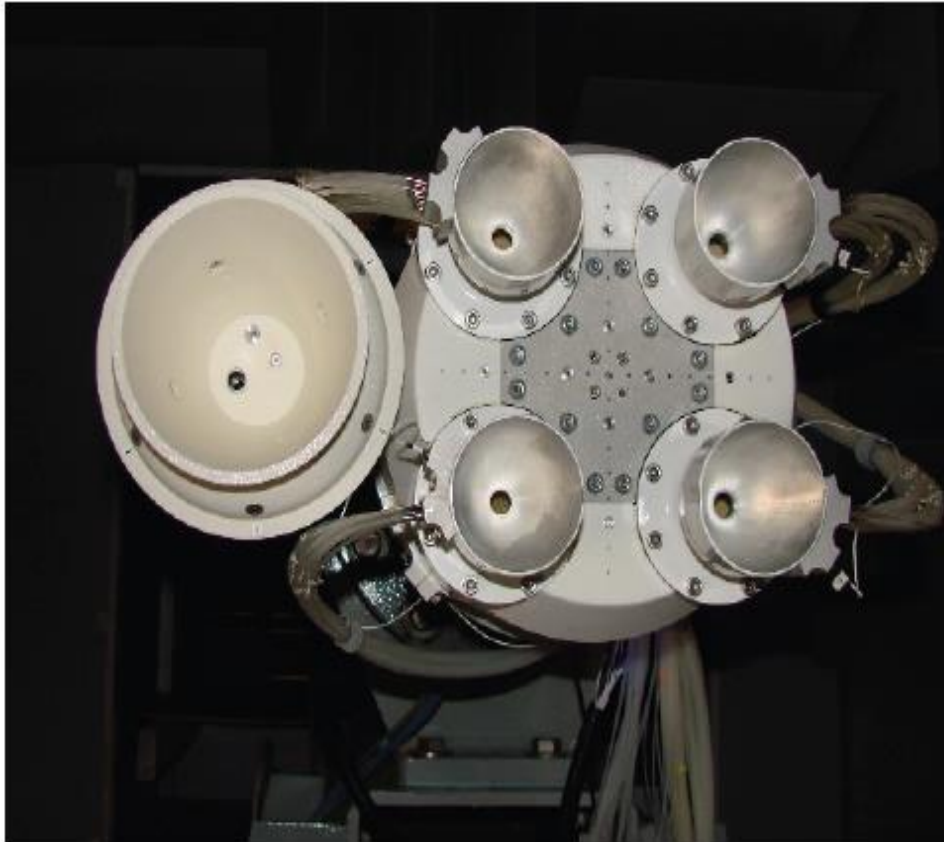


	N/A	3/27/2014
	N/A	3/27/2014
	N/A	9/24/2020



Provided acoustic environment in terms of  $R$ ,  $\beta$ , and  $\varphi$ .





- Launch duct geometry added later (2016)
- Designed to reproduce the same unsteady flow phenomenon as occurs on startup of RS-25 (SSME)
- Startup of 4 engines versus 3
- Acoustic env. on booster nozzle plug (relative to orbiter base heat shield)

- Acoustics scales w/ Strouhal no. for frequency
- Amplitude scales with thrust
- Atmospheric attenuation
- Size limits to nozzle scaling
- Deflected noise is directional/ lobed
- As rocket elevation increases, noise spectrum peak shifts left
- Multiple nozzles have effective nozzle diameter
- Sound energy is proportional to the kinetic exhaust stream energy
- Self noise and Mach noise
- Noise doubling and Correlation aspects of liftoff noise
- Crackling requires high Mach number flow
- Non-linear spectral correlation at distance from max noise (sonic termination)

- Scale models first used to measure launch acoustics sensitivity to deflector and duct configurations
- Key scaling characteristics quickly realized
- Knowledge gained from generic acoustic models used to inform preliminary design
- Acoustic models eventually used to predict launch acoustics
- Multitude of tests gave insight to physical processes for noise production and propagation
- Acoustic models used for other launch environments, e.g., ignition overpressure, hydrogen pop, debris transport model validation, etc.
- Vibroacoustic community has need for improved characterization of the acoustic field generated by the propulsion system
  - Ratio of diffuse to propagating field,  $R$
  - Decay coefficient,  $\beta$
  - Angle of incidence,  $\varphi$

- Detailed modeling and simulation is a now part of launch acoustic environment definition process
  - Solid motor internal ballistics
  - Transient nozzle exhaust flow (liquids and solids)
  - 3-D HRLES plume
  - 3-D DGS for nonlinear CAA
  - Water spray systems
  - DTA
- Validation via scale models and full scale launches
- Provides high fidelity insight
  - To interpret scale model results
  - To assess launch pad design details/ modifications